Outdoor flight activity and immigration of *Rhyzopertha dominica* into seed wheat warehouses

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Abstract

The flight activity of lesser grain borer, *Rhyzopertha dominica* F. (Coleoptera: Bostrichidae), was monitored at two Foundation seed wheat warehouses during the 2003 and 2004 field seasons, using pheromone-baited Lindgren funnel traps positioned indoors and outdoors. General stored-product insect activity was also monitored using unbaited sticky traps positioned inside the warehouses around overhead doors. Pheromone-baited traps were useful for monitoring *R. dominica* activity, however insect captures decreased when lures were not changed weekly. Flight peaks were documented in early May and again from September through October, and insect captures inside warehouses correlated with timing of outdoor captures. Multiple regression analyses showed that slightly more than half of the variability in *R. dominica* captures could be explained by mean ambient air temperature and wind speed during the 2 h preceding sunset. Stored-product Coleoptera captured on unbaited glue boards around overhead doors included *Ahasverus advena, Cryptolestes ferrugineus, R. dominica, Sitophilus oryzae, Tribolium castaneum*, *Trogoderma variabile*, and *Typhaea stercorea.* Door gaskets significantly reduced the number of insect captures on glue boards placed around the overhead doors, and generally restricted their entry to ground level. These studies demonstrated that outdoor pheromone-baited traps are effective monitoring tools for determining when grain-handling facilities are most susceptible to infestation and that exclusion may be an effective component of a pest management program.

Introduction

The lesser grain borer, *Rhyzopertha dominica* F. (Coleoptera: Bostrichidae), is a devastating cosmopolitan pest of stored grain, grain products, and other materials (Potter, 1935). This insect can penetrate many types of packaging material including seed sacks (Highland, 1984), and both larvae and adults consume grain-based products resulting in fragmented kernels, powdery residues, and a characteristic pungent odor. The complete lifecycle requires approximately 1 month under typical USA summer environmental conditions (Birch & Snowball, 1945; Howe, 1950) and mated females produce hundreds of eggs. Infestations are difficult to detect because immatures develop inside grain kernels and the adults are inconspicuous and move little once in the grain making detection with traps difficult (Fargo et al., 1989; Vela-Coiffier et al., 1997). Newly emerged adults bore out of the host wheat kernels leaving behind insect damaged kernels (IDK), a quality factor specified in grain contracts and used to restrict low quality (sample grade) grain from entering the human food supply (GIPSA, 1993).

There is little evidence that *R. dominica* infests wheat in the field (Hagstrum, 2001); therefore, infestation in storage results from either a failure to remove residual populations from storage structures or from dispersing individuals exploiting unprotected stored grain. *Rhyzopertha dominica* is a strong flier that is commonly captured near grain elevators and farm storage bins in Kansas (Dowdy & McGaughey, 1994, 1998). Flight initiation has been studied in the laboratory (Perez-Mendoza et al., 1998, 1999a,b). Hagstrum (2001) showed that *R. dominica* and other stored-product pests can immigrate into grain bins through the

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eaves, vents, and poorly sealed bin bottoms. Other species of stored-product insects have been detected immigrating into warehouses and flour mills and population changes inside structures have been correlated with outdoor population trends (Campbell & Arbogast, 2004; Campbell & Mullen, 2004). Trapping with pheromone-baited traps is an effective method for detecting and estimating relative abundance of stored-product insects during the dispersal phase (Burkholder, 1984), and *R. dominica* readily responds to a commercially available aggregation pheromone. Studies on the diel periodicity of *R. dominica* show that a small flight peak occurs at dawn and then a much larger peak occurs just before sunset (Leos-Martinez et al., 1986). Comparatively little dispersal takes place during the day when buildings may be open to facilitate transfer of product. These findings suggest that sanitation combined with proper sealing of the structures may help safeguard grain from this serious pest and reduce the need for chemical insecticides.

Current pest management programs for *R. dominica* are designed for managing insects in the grain. Extension recommendations for stored grain insects specify sanitation of empty storage facilities and use of a residual surface treatment, insecticide seed treatments, grain temperature management, routine insect monitoring utilizing a grain trier or traps, and subsequent fumigation when an insect infestation develops (Higgins, 1987; Lippert & Higgins, 1989; Reed et al., 1995; Sloderbeck et al., 2002). Decision support software (Flinn et al., 2003) can be useful for interpreting sampling data and producing a risk analysis report. Organophosphorous insecticide seed treatments break down rapidly under summer storage conditions, and *R. dominica* has developed resistance to some of the commonly used products such as malathion and chlorpyrifos-methyl (Champ & Dyte, 1977; Haliscak & Beeman, 1983; Horton, 1984; Zettler & Cuperus, 1990). Sampling wheat in bins is laborious and the tolerance for damage to high value commodities, i.e., seed wheat, is low. Large numbers of spear samples (200+) are required to truly estimate stored-product insect population density (Hodges et al., 1985).

Limited published data are available pertaining to seasonal flight activity, routes of immigration into warehouses, and use of the commercially available pheromone in monitoring programs for insects such as *R. dominica*. Better knowledge of pest behavior and population dynamics is needed for developing novel control strategies and for precisely targeting pest management tactics. Pheromone-baited traps have been a practical monitoring device for tracking outdoor populations of *Prostephanus truncatus* (Hodges, 2002), a closely related member of the Bostrichidae, but information on long-term outdoor monitoring of *R. dominica* around grain storage facilities is limited (Throne & Cline, 1991; Dowdy & McGaughey, 1998). Birkinshaw et al. (2002) demonstrated similarity between outdoor captures and incidence of store infestations with *P. truncatus*. Climatic data have been used previously to predict stored-product pest dispersal and immigration (Borgemeister et al., 1997; Nansen et al., 2001; Hodges et al., 2003), however, the basic biology of *R. dominica* outside of grain storage facilities is undocumented.

Waiting until insects arrive in the grain or warehouse may not be the most effective pest management strategy, especially for bagged commodities in warehouses where direct grain sampling is difficult due to the large quantity of grain and vast number of bags. We propose that outdoor monitoring and targeted intervention strategies such as exclusion may be viable alternatives to assist mitigating pest infestations. The objectives of the current study were to: (i) study seasonal patterns in *R. dominica* flight activity, (ii) determine periods of time when warehouses were susceptible to infestation from outside sources, (iii) investigate the importance of doors as routes of entry into warehouses, and (iv) test the effectiveness of exterior door gaskets around overhead doors for mitigating insect immigration.

Materials and methods

Warehouses

Studies were conducted in and around foundation seed warehouses located at Manhattan, KS, USA, and Mead, NE, USA. The mission of these operations is to propagate Hard Red Winter wheat of new varieties and maintain a source of genetically pure existing varieties. Although there were agronomic production fields located within 50 m of each warehouse, there were many differences between locations pertaining to construction, management practices, and other biologically important attributes (Table 1). Wheat seed was generally harvested in early summer and then stored in small steel storage bins for only few weeks until the seed could be cleaned, treated with chlorpyrifos-methyl (Reldan® 4E, Gustafson LLC, Plano, TX, USA) and bagged. After the wheat seed was sold in October, the warehouses were sealed and fumigated with phosphine (aluminum phosphide) to manage residual populations of stored-product insects.

Trapping methods

A multidimensional insect monitoring program was initiated to document insect flight inside and around the seed warehouses. Lindgren funnel traps (4-funnel size) (Phero Tech Inc., Delta, BC, Canada) (Lindgren, 1983) were modified by replacing the stock mesh screen in the collection reservoir with a stainless steel mesh containing 420 µm openings. Traps were placed in cardinal directions at distances of 0, 50, 100, and 150 m from each warehouse

Table 1 Physical and cultural description of the study sites.

	Location	
Descriptor	Manhattan, KS	Mead, NE
Location	39.19010°N, 096.58998°W	41.22910°N, 096.48939°W
Primary production in area	Wheat	Corn
Other storage in warehouse	Oats, soybeans, sorghum, and canola	Corn and soybeans
Primary storage method	27.2 kg paper bags	1.1-tonne cloth bags
Warehouse construction date and type	1996; steel, insulated walls and doors, no windows	1943; wood and brick, poorly sealed doors and windows
Vegetation barrier around warehouse	None	Concrete, 3 m wide
Distance from warehouse to nearest grain bins	25 m	780 m
Surrounding community	Urban; apartments and farm offices	Rural; crop and range land
Crack and crevice insecticide treatments	None	Cyfluthrin (June application only)
Nearby (<50 m) tree rows	*Juniperus virginiana* and *Pinus nigra*	*Juniperus virginiana* and *Pinus nigra*

with two additional traps placed among the on-site grain bins at Mead, and three additional traps among the grain bins at Manhattan. The innermost traps were placed along the warehouse foundation at Manhattan but against the outer edge of the concrete walkway at the Mead facility. Outdoor Lindgren traps were suspended from trap holders constructed from 1.3 cm diameter steel rod such that the top of the trap was 1.4 m above the ground.

Warehouses were each provisioned with two funnel traps suspended from the ceiling (3.7–4.0 m above ground level) and six Storgard II sticky traps (Trécé Inc., Adair, OK, USA) at 1.6–1.8 m above ground. Storgard II sticky traps are diamond-shaped cardboard traps with a total sticky area of 300 cm^2. Funnel traps were located near the center of each warehouse and had to be located above ~4 m so that forklifts could move freely. The male-produced aggregation pheromone of *R. dominica* (Williams et al., 1981), released from rubber septa, was used in both Lindgren and Storgard II sticky traps. Pheromone lures were replaced every 3–4 weeks starting in July 2003, and then every other week from late August through the remainder of the 2003 field season. Lures were replaced weekly throughout 2004. All traps were serviced weekly commencing in late July and lasting through mid October 2003, and from late April through November 2004. Outdoor traps at Manhattan were serviced each weekday during the 2004 season. Six representative *R. dominica* specimens, voucher number 164, were deposited in the Kansas State University Museum of Entomological and Prairie Arthropod Research, Department of Entomology, Kansas State University, Manhattan.

During August and September of the 2004 field season, spilled grain found under pallets and cleaning equipment was sampled for insect activity. Technicians collected ~250 g samples any time grain debris was observed during the weekly sampling visits. The samples (generally 1–2 samples per week) were brought to the laboratory, weighed, and sieved to separate insects from the grain.

Environmental monitoring

Outdoor environmental conditions were monitored using electronic data loggers. A 2-m-tall weather station outfitted with sensors measuring temperature, relative humidity, wind speed and direction, barometric pressure, and solar radiation (part numbers H21-001, S-THA-MOXX, S-WCA-M003, S-BPA-CM10, and S-LIB-M003; Onset Computer Corp. Pocasset, MA, USA) was positioned in an open area at each site. The solar radiation sensor had a measurement range of 0–1280 W m^{-2} in a spectral range of 300–1100 nm; however, individual spectra could not be extracted from the dataset. Loggers recorded data every 15 min throughout the study.

Exclusion method

The gap between overhead doors mounted on a track and the opening in the building was targeted for investigation as a possible route of insect entry. Exterior vinyl door gaskets (part 777 W, WJ Dennis and Co., Elgin, IL, USA) were installed on one side of each of the two doors at Mead during the 2004 field season. The opposite side of each door was left without the gasket to test if installation of gaskets decreased insect immigration. Gaskets extended from the ground to the top of the door on one door and on the oppose side of the second door. The recently constructed Manhattan warehouse already had vinyl door gaskets installed on the sides of the doors. Gaskets have a flexible leaf that floats against the face of the overhead door and are designed to keep wind and rain out.

Small gaps between the door and the doorjamb around overhead doors leading into each warehouse were monitored using unbaited glue boards (Trapper® MAX, Bell Laboratories Inc., Madison, WI, USA) during 2004. Traps were fastened using grey duct tape to the interior side of the doorjamb such that insects moving through the gap might become trapped. One trap was placed flat on the floor and then 10 successive traps were placed one above the other to a height of 200 cm from the ground on each side of two doors per warehouse. Three additional traps were placed along the top of the overhead doors. Traps were replaced monthly or sooner if a large number of insects or dust adhered to the glue boards thereby affecting trap efficiency. Personnel servicing the glue boards wore disposable gloves to avoid pheromone contamination if they also serviced the Lindgren traps during the same visit.

Statistical analyses

In the studies of pheromone longevity and its effect on *R. dominica* capture, data were blocked by pheromone placement date and then modeled using repeated measures ANOVA (PROC MIXED, SAS Institute, 1999) with weeks or days since pheromones were deployed as the treatment variable and insect captures as the response variable; the unstructured covariance model was the most effective to model the intrasample correlation (Littell et al., 2002). Single degree of freedom orthogonal contrasts blocked by pheromone placement date were used to document overall easting or northing directional effects. Likewise, the effect of trap distance from the warehouse was analyzed independently with the same procedure. In 2003, data collected after 14 October at Manhattan or 8 September at Mead were not included in the statistical analyses since cool weather suppressed captures. In 2004, only daily captures between 1 June and 8 November were analyzed statistically. Indoor *R. dominica* captures in Lindgren funnel traps and unbaited glue boards were related to mean outdoor captures by week using correlation analyses (Pearson, 1920). Finally, paired comparisons between insects captured on unbaited traps compared with insects on unbaited traps protected by vinyl door gaskets were modeled using ANOVA because there were not enough captures to conduct mixed model analyses. All captures in pheromone-baited traps were log transformed [log(Y + 1)] because the standard deviations were proportional to the means (Steel & Torrie, 1980).

Multiple response models to identify environmental factors influencing *R. dominica* captures in outdoor Lindgren traps were developed using data reduction methods and multiple regression. Mean daily *R. dominica* captures could be grouped roughly into three distinct seasons; spring (late April through May) and autumn (15 August through November) captures were highly variable, while less variation occurred during the summer (June through 15 August). Separate models were created for summer and autumn seasons, but spring captures were too variable to correlate with environmental conditions. Prior to model building, data reduction was accomplished by plotting each independent weather variable against mean daily *R. dominica* capture to eliminate conditions that completely suppressed flight (i.e., low temperature). Regression models were built using PROC REG (SAS Institute, 1999) with the STEPWISE and BACKWARD options. Significant environmental variables in the preliminary analyses were examined for possible correlations with each other using PROC CORR (SAS Institute, 1999); when variables were correlated with each other the weaker variable was removed. Environmental data used in the model were obtained by daily averaging across a time period from 1 to 3 h before sunset in order to smooth anomalous data points that occurred when modeling was conducted with only the single data point occurring at the hypothetical flight peak.

Results

The pheromone lure was useful for monitoring *R. dominica* activity, however the lure replacement interval was observed to have a significant effect on outdoor captures. A total of 1316 *R. dominica* were captured in outdoor traps at Manhattan in 2003; by comparison, 4412 *R. dominica* were captured during the same time frame in 2004. During 2003, when lures were replaced every 3–4 weeks through September and then every 2 weeks for the rest of the field season, there were significant differences among captures by week (Manhattan: $F_{3,61} = 40.5$, $P<0.01$; Mead: $F_{2,29} = 131.5$, $P<0.01$) (Figure 1). There was a greater than four-fold decrease in captures between the first 2 weeks of pheromone placement, regardless of location. The decrease at Manhattan between week 1 (9.2 ± 1.3; n = 64) and week 2 (1.7 ± 0.4 captures/trap/week; n = 61) was significant ($F_{1,61} = 77.5$, $P<0.01$). Likewise, the same relationship between week 1 (20.4 ± 1.8; n = 32) and 2 (4.8 ± 0.8 captures/trap/week; n = 32) was observed at Mead ($F_{1,29} = 119.4$, $P<0.01$). To overcome this perceived loss of pheromone attractiveness, lures were changed weekly while traps were checked daily in Manhattan in 2004. However, mean *R. dominica* captures were greater on the first day (3.1 ± 0.4) than day 2 (1.6 ± 0.2), 3 (1.0 ± 0.1), or 7 (1.8 ± 0.2 captures/trap/day; n = 283) ($F_{3,285} = 14.2$, $P<0.01$).

Directionality trends and the effect of trap distance from the warehouse were never significant at Mead, but had variable effects on mean trap captures at Manhattan. A significant effect attributed to trap distance from the warehouse was observed in the north–south transect in both 2003 and 2004 ($F_{1,61} = 6.2$, $P = 0.02$ and $F_{1,285} = 7.0$, $P<0.01$, respectively); captures increased with distance from the warehouse.

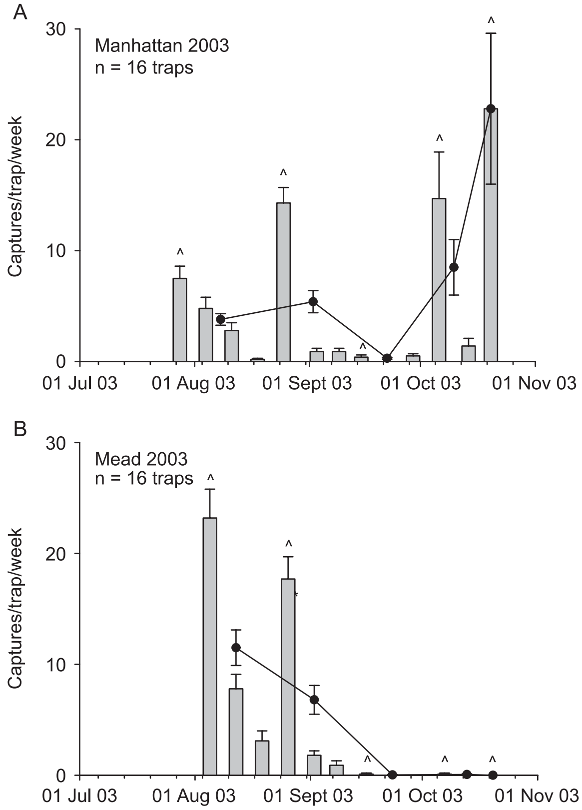

Figure 1 Weekly mean + SEM *Rhyzopertha dominica* captures in pheromone-baited Lindgren funnel traps located outdoors at (A) Manhattan, KS in 2003 and (B) Mead, NE in 2003. Line graph indicates the mean captures ± SEM within pheromone replacement intervals. Circumflexes (^) indicate replacement of pheromone lures.

Likewise there were significantly more individuals captured farther from the warehouse in the east–west transects ($F_{1,285} = 6.7$, $P = 0.01$) in 2004. The northing directional effect was significant in 2004 ($F_{1,285} = 7.0$, $P<0.01$) because there were comparatively fewer captures north of the warehouse. All remaining comparisons were not significant.

One difference was observed between traps placed near the grain bins and the remaining outdoor traps during the study. At Mead, there was not a difference in 2003 ($F_{1,34} = 1.0$, $P = 0.33$), but there was a significant difference in 2004 ($F_{1,106} = 7.5$, $P<0.01$) with more captures in traps placed near bins (14.08 ± 2.6; n = 46) compared with captures in the remaining outdoor traps (6.2 ± 0.5 captures/trap/week; n = 380). This difference manifested primarily from early July through the first week in August. At Manhattan, there were no observed differences in 2003 ($F_{1,74} = 0.7$, $P = 0.41$) or 2004 ($F_{1,340} = 0.5$, $P = 0.47$).

Distinct seasonal peaks were observed in *R. dominica* captures. At Manhattan in 2004, an extraordinarily large number of captures were documented during early and mid-May, and then the rate of captures tailed off to a fairly consistent level between 1 June and 15 August (Figure 2). From late August through October relatively large numbers of captures were recorded intermittently before ending in mid-November. In comparison, *R. dominica* captures at Mead in 2004 started in late May and built up to a peak in mid-July. Mean captures then fluctuated between two and 10 until cooler temperatures in October inhibited flight (Figure 3).

Data reduction methods prior to multiple regression model building were conducted to eliminate data in which a single factor prevented flight and subsequent insect capture. In the summer model, no captures occurred when wind speed exceeded 5 m s^{-1} or when temperature was less than 22.5 °C. Likewise, no captures occurred during the autumn when wind speed was greater than 6 m s^{-1} or when temperature was less than 17.5 °C. Multiple regression modeling showed that temperature and wind speed were the strongest factors influencing captures during summer, whereas wind speed and dewpoint were the most important during autumn flights (Table 2). The relationship between data for environmental variables and mean daily *R. dominica* captures was stronger during summer than during autumn.

Although fewer *R. dominica* were captured inside the warehouses than outside, the trends were similar to those of outdoor traps. Lindgren traps positioned inside the Manhattan warehouse (Figure 2C) had a peak in *R. dominica* captures in mid-May and October while Storgard II traps placed in the warehouse detected insects at approximately the same time (Figure 2D). There was a strong positive correlation between mean outdoor captures and indoor captures in Lindgren traps ($r = 0.99$, $P<0.01$; n = 28) and in Storgard II trap ($r = 0.97$, $P<0.01$; n = 28). In contrast to Manhattan, few *R. dominica* were captured indoors at

Table 2 Multiple regression estimates for predicting mean daily *Rhyzopertha dominica* captures in pheromone-baited Lindgren funnel traps near the Manhattan, Kansas Foundation wheat seed warehouse in summer and autumn.

Variable	Estimate ± SEM	Partial R^2	F	P
Summer[1]				
Intercept	−2.30 ± 0.81			
Temperature (°C)	0.14 ± 0.03	0.45	23.55	<0.01
Wind speed (m s^{-1})	−0.34 ± 0.11	0.13	8.84	<0.01
Autumn[2]				
Intercept	6.14 ± 2.72			
Wind speed (m s^{-1})	−2.35 ± 0.70	0.23	9.33	<0.01
Dew point	0.35 ± 0.13	0.14	6.85	0.01

[1]$F_{2,28} = 19.38$, $P<0.01$; $R^2 = 0.58$.
[2]$F_{2,31} = 8.95$; $P<0.01$; $R^2 = 0.37$.

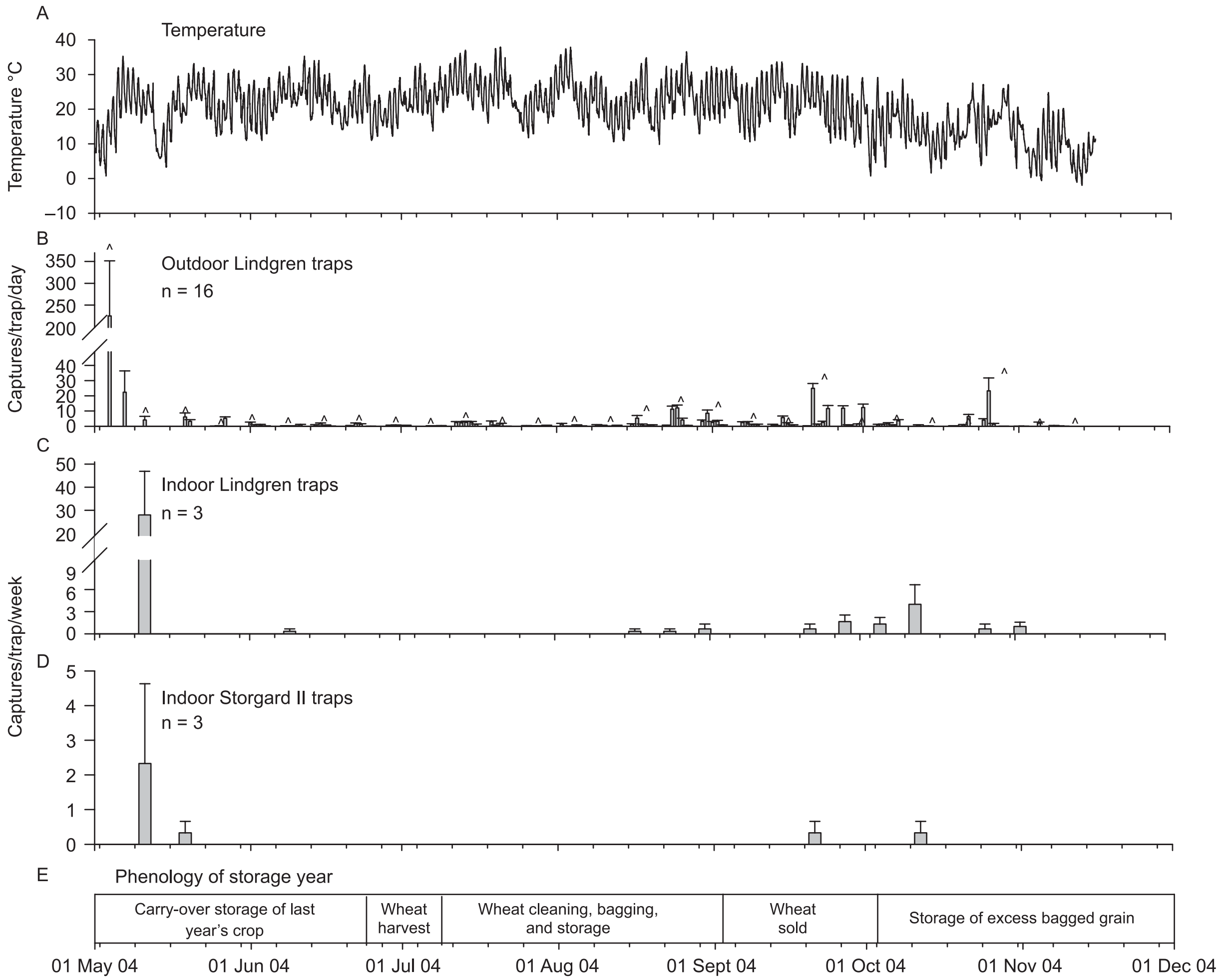

Figure 2 (A) Daily temperature and mean + SEM *Rhyzopertha dominica* captures in (B) outdoor Lindgren traps, (C) indoor Lindgren traps, (D) indoor Storgard II traps, and (E) phenology of activities during the 2004 field season at Manhattan, KS. Circumflexes (^) indicate replacement of pheromone lures.

Mead (Figure 3C–D). Only four insects in Lindgren funnel traps and three in Storgard II traps were captured all year. Correlations were not significant between outdoor and indoor Lindgren traps ($r = 0.27$, $P = 0.20$; $n = 24$) or Storgard II traps ($r = -0.04$, $P = 0.87$; $n = 20$).

Captures of stored-product Coleoptera on unbaited glue boards positioned adjacent to overhead doors indicated that this is an important route of entry for insect infestations. At Manhattan in 2004, stored-product Coleoptera captured included *Ahasverus advena* (Waltl), *Cryptolestes ferrugineus* (Stephens), *R. dominica*, *Sitophilus oryzae* (L.), *Tribolium castaneum* (Herbst), *Trogoderma variabile* Ballion, and *Typhaea stercorea* (L.). The temporal distribution of *R. dominica* captures on unbaited glue boards was highly correlated with weekly capture of *R. dominica* in outdoor pheromone-baited traps ($r = 0.918$, $P<0.01$; $n = 27$). Captures of *A. advena* and *C. ferrugineus* peaked in early September and then tapered off through early November (Figure 4). Other economically important species, including *S. oryzae* and *T. castaneum*, generally were captured starting in late August and into the autumn months. *Typhaea stercorea* was captured at low densities throughout the study. Between 3 and 16 times more insects were captured on floor traps than traps placed 2–19 cm above the floor (Figure 5). Captures generally decreased with increasing height above the floor; no beetles were ever captured on traps placed above the overhead doors. More than three times the number of *R. dominica* were captured at floor level than all other locations combined.

At Mead in 2004, stored-product Coleoptera captured included the same species listed above for the Manhattan location, but there were only 180 individuals captured compared with nearly 600 at Manhattan. While 104 *R. dominica* were collected on unbaited sticky traps at

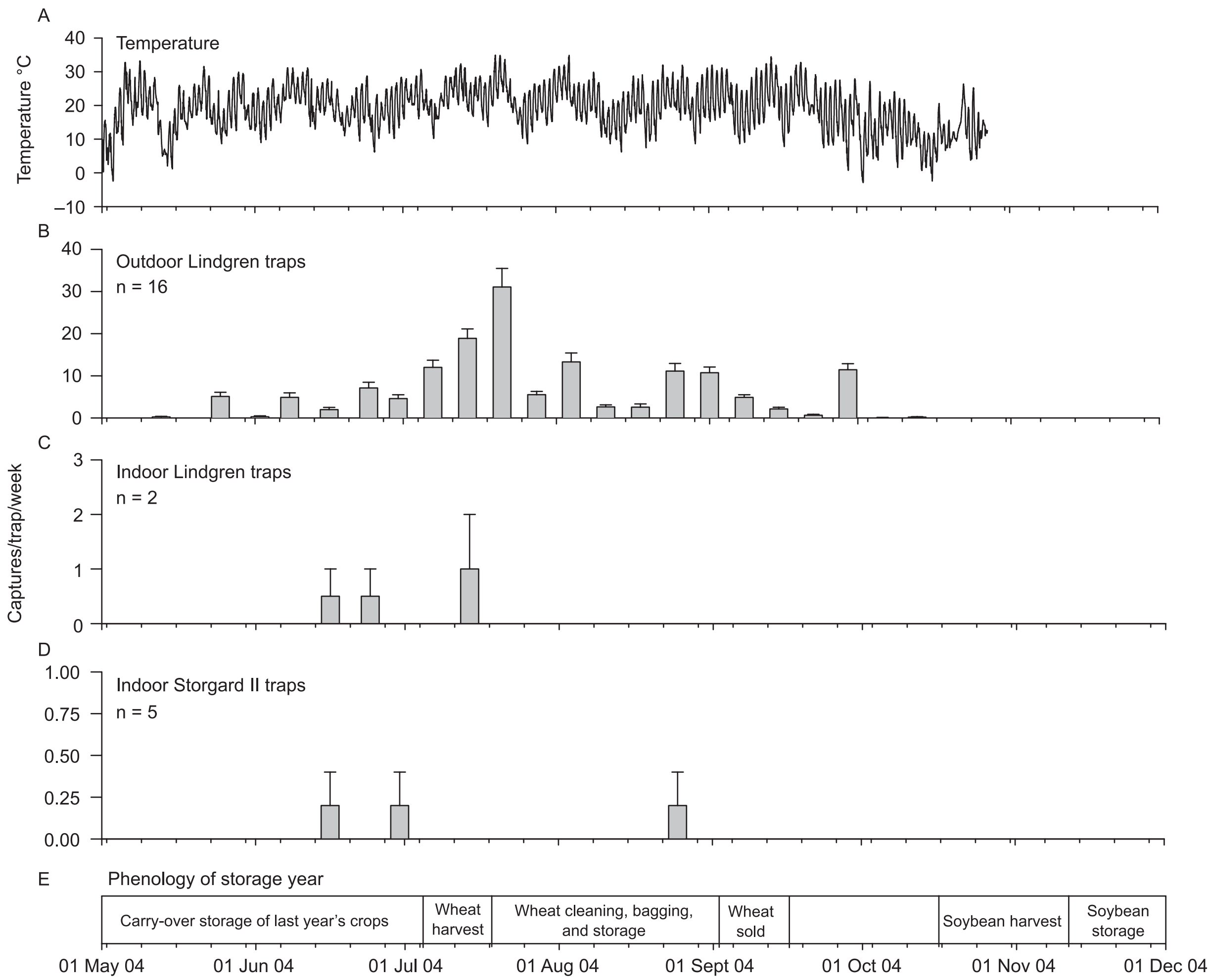

Figure 3 (A) Daily temperature and mean + SEM *Rhyzopertha dominica* captures in (B) outdoor Lindgren traps, (C) indoor Lindgren traps, (D) indoor Storgard II traps, and (E) phenology of activities during the 2004 field season at Mead, NE.

Manhattan, only five were collected in Mead. However, unbaited glue boards placed on the floor were missing or moved during every sampling interval from 16 June through 3 August at Mead, likely the result of a persistent small mammal infestation. This time interval accounted for >60% of the *R. dominica* captures in the outdoor traps and all but one capture in the indoor pheromone-baited traps. The gaskets significantly decreased the total captures of all beetles from 125 insects on the side of the doors without gaskets to 55 insects on the side of the doors with gaskets ($F_{1,972} = 11.1$, $P<0.01$). These reductions were always significant, by species, if more than 15 insects of that species were captured over the entire year (Table 3).

Direct samples of spilled wheat collected in the warehouses and cleaning rooms did not yield any *R. dominica* at either location. Little spilled grain occurred in the warehouses, so many of the grain samples were taken from under the cleaning equipment. At Manhattan, a total of 11 samples were collected ranging from 35 to 464 g in quantity. The only stored-products insects recovered in the grain samples were two *S. oryzae* on 14 September. At Mead, no stored-product insects were recovered in any of the six samples ranging 98–800 g.

Table 3 Sum captures of stored-product Coleoptera on non-baited glue boards at Mead, NE in 2004.

Insect species	Sum captures without gaskets	Sum captures with gaskets	F^1	P
A. advena	6	0	4.66	0.03
C. ferrugineus	83	33	7.22	<0.01
R. dominica	4	1	1.89	0.17
T. castaneum	4	0	1.65	0.20
T. stercorea	4	11	1.61	0.21
T. variabile	24	10	4.12	0.04

[1]Degrees of freedom for each test were 1972.

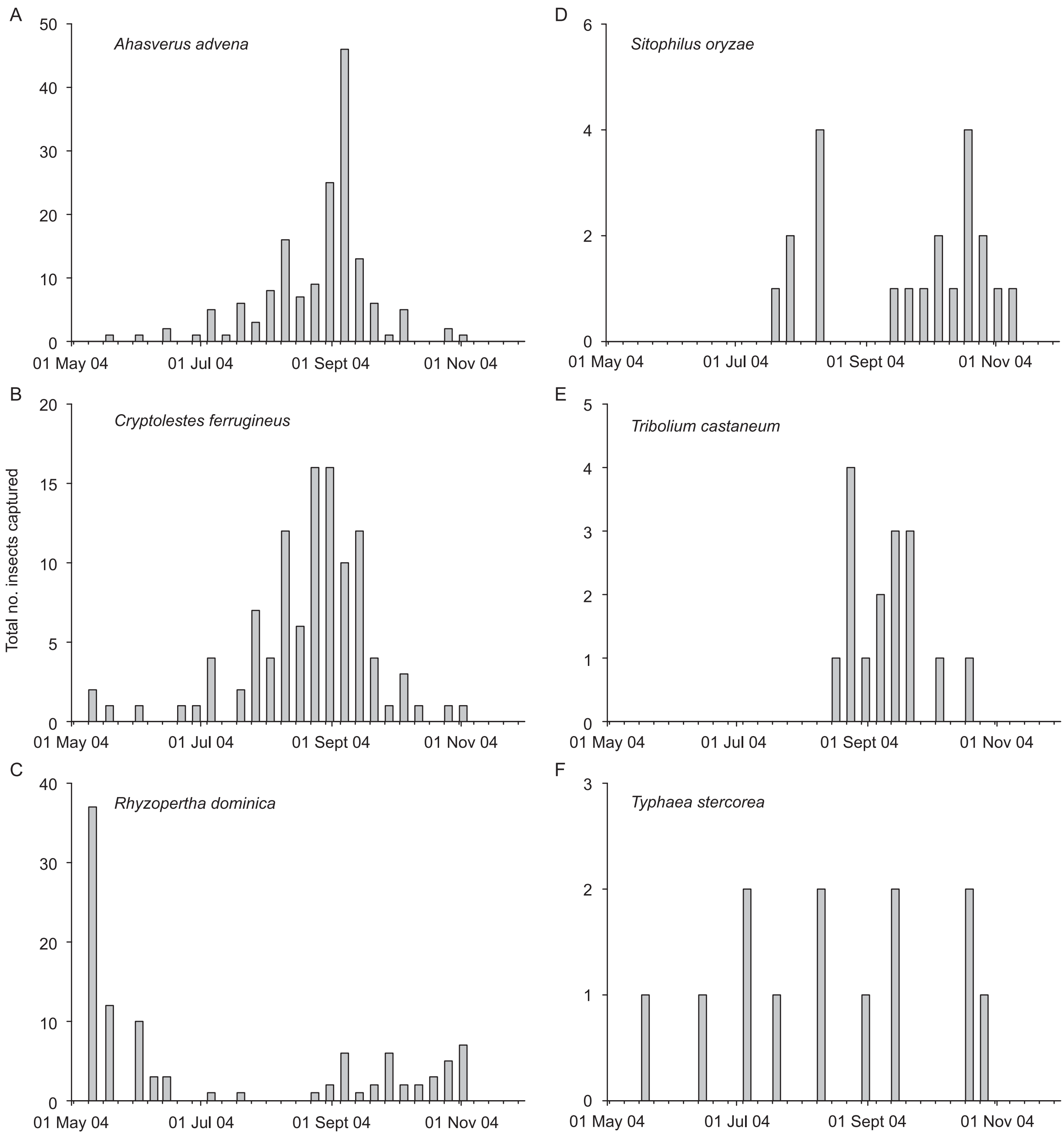

Figure 4 Temporal distribution of insect captures including (A) *Ahasverus advena*, (B) *Cryptolestes ferrugineus*, (C) *Rhyzopertha dominica*, (D) *Sitophilus oryzae*, (E) *Tribolium castaneum*, and (F) *Typhaea stercorea* on unbaited glue boards at Manhattan 2004. All doors had vinyl door gaskets on both sides.

Discussion

The responses of *R. dominica* to the pheromone lures decayed rapidly during 2003. This is an important consideration because insect response should be similar, or at least well understood, before making comparisons about population changes. Daily trap servicing during 2004 provided better resolution during the first week to show that flight response on the first day was significantly greater than during the remaining days within the first week. One way to mitigate the effects of the stronger first day would be to 'age' the lures for at least 24 h before deploying them in the field as suggested for polyethylene lures for *P. truncatus* (Hodges et al., 2004). Similar observations about first day captures

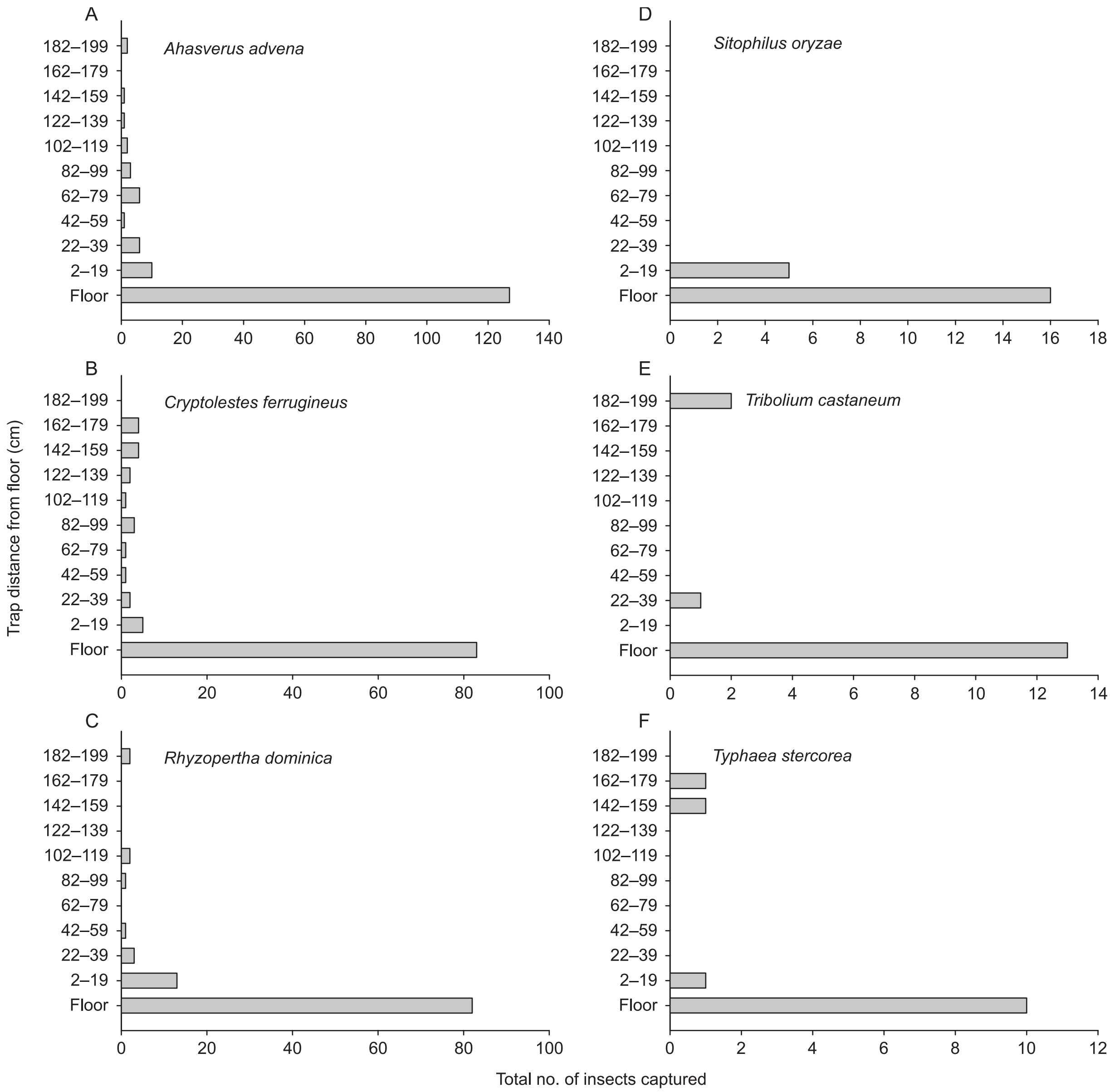

Figure 5 Vertical distribution of insect captures including (A) *Ahasverus advena*, (B) *Cryptolestes ferrugineus*, (C) *Rhyzopertha dominica*, (D) *Sitophilus oryzae*, (E) *Tribolium castaneum*, and (F) *Typhaea stercorea* on unbaited glue boards at Manhattan 2004. All doors had vinyl door gaskets on both sides.

and pheromone lures have been observed for other species (e.g., Ramaswamy et al., 1983, 1985). This problem could potentially be alleviated with dispensers or formulations that provide more consistent, long-term pheromone release, since *R. dominica* pheromone components do not degrade with time (Cogburn et al., 1984). Leos-Martinez et al. (1987) showed that the pheromone could last up to 30 days when dispersed through polyethylene microcentrifuge tubes. However, the two components of the pheromone blend have different diffusion rates, each related to temperature (Cogburn et al., 1984).

While trap position was significant in some cases, there were few predictable trends. Situated in an urban setting, the Manhattan warehouse was surrounded by trees and wheat fields. In contrast, the Mead site was surrounded on all sides by tall corn plants for most of the summer. Differences in trap microclimate and airflow around the traps are plausible factors to explain differences in trap captures.

For example, Manhattan had no significant effect of distance from warehouse on trap capture, but a significant difference was observed in Mead. This could be due to the fact that the innermost outdoor traps were placed directly against the warehouse in Manhattan, whereas at Mead the concrete walkway precluded trap placement directly adjacent to the warehouse. Beetles fly upwind to pheromone sources and flight speed increases with altitude (Fadamiro et al., 1998), so it logically follows that traps located even a few meters away from the building likely received better airflow resulting in increased trap efficiency.

In the USA, the majority of *R. dominica* flight captures occurred in a broad peak starting 4 h before sunset, peaking 1 h before sunset, and ending 2 h after sunset (Leos-Martinez et al., 1986). In Australia (Barrer et al., 1993; Wright & Morton, 1995), this peak was characterized starting 5 h before sunset, peaking 2 h before sunset, and ending 1 h after sunset. Laboratory experiments of Bashir et al. (2003) suggested elevated pheromone production during the last hours of photophase. It may be concluded from these studies that peak activity of *R. dominica* occurs approximately 3 h before sunset. Pheromone trap captures of this species were modeled using data from environmental variables occurring in the peak of that timeframe, which occurred from 1 to 3 h before sunset.

Modeling mean *R. dominica* captures as a function of environmental variables showed that daily weather variables explained approximately half of the variation. Nang'ayo (1996), using a similar method, found that weather variables explained 7% of the total variance in captures of the closely related *P. truncatus*, while Borgemeister et al. (1997) explained 30% of their trap catch variation with environmental variables. Other factors known through laboratory experiments to influence *R. dominica* flight initiation include age, starvation, density, frass accumulation, light intensity, strain, scotophase, and diet (Barrer et al., 1993; Aslam et al., 1994; Dowdy, 1994; Perez-Mendoza et al., 1998, 1999a,b). The authors hypothesize that physiological state (age, feeding, mating, and reproductive status) of the individual may be the missing component to understanding the temporal dynamics of dispersal in this species. Ovarian development would be one possible measure of the propensity for an individual to disperse. Future studies should assess feeding and reproductive status to glean additional data that may be helpful for predicting immigration, improving models, and ultimately protecting grain and grain-related products.

Differences in the lower temperature threshold for *R. dominica* flight activity in the autumn vs. summer conditions may, in part, explain variable reports in the literature. In Australia, Wright & Morton (1995) found that 16 °C was the minimum temperature threshold for flight, but Sinclair & Alder (1984) estimated a threshold of 21.5 °C. Dowdy (1994) reported a lower flight threshold of 19.9 °C in the USA. Decreased lower flight thresholds as a result of cooler seasons are also reported in other species (Castrovillo & Cardé, 1979). This change may be a result of hormonally induced physiological changes or a generational effect. It seems plausible that the increase in fall flight observed in *R. dominica* is due to a new generation of adults that have developed during the summer. Aslam et al., 1994) showed that long scotophases (L6:D18) delay development, increase egg production, and reduce flight compared to shorter scotophases. This hypothesis is bolstered by the knowledge that recently emerged adults are more responsive to influences stimulating flight (Barrer et al., 1993).

The importance of pest immigration into grain and food processing facilities is becoming more widely appreciated. Pest management professionals rely on exclusion of pests (Osmun, 1984) as an important component of integrated pest management, but the practical efficacy of exclusion has not been studied. The importance of sealing to mitigate pest infestation has been suggested by self-mark and recapture studies in grain processing facilities (Campbell & Arbogast, 2004; Campbell & Mullen, 2004), but has not been characterized. This is the first project to document a methodical evaluation of insect immigration into warehouses. The discovery of insect capture on the glue boards placed in the gaps between overhead doors and frames is particularly indicative of the importance of immigration; however, we acknowledge that this approach, by itself, cannot determine the direction of movement of the insects, i.e., from inside to outside or outside to inside. Direction of movement will have to be confirmed by other methods such as mark and recapture.

These data demonstrate that there are opportunities to manage potential pest problems prior to grain infestation. Inclusion of outdoor monitoring in pest management programs will enable management activities to be more proactive. Vinyl gasket installation around overhead doors decreased the overall number of insects entering facilities and constrained major coleopteran species (i.e., *T. castaneum* and *R. dominica*) from entering the warehouse primarily at ground level. Although we did not evaluate gaskets placed under overhead doors, such exclusionary barriers could further decrease insect immigration. Further research on the benefits of additional sealing by pest management professionals would be a highly effective tactic.

The biology and ecology of *R. dominica* in the extant literature pertain specifically to immigration into and reproduction in storage, but key data on the overwintering lifestage, possible overwintering sites out of grain, and alternative feeding sites are conspicuously absent. These data suggest that the species overwinters in the adult stage because large numbers of adult beetles were captured early in the year when temperatures are not sufficiently high enough for immature stages to develop into adults. Bulk grain warms slowly and would likely not be warm enough to permit insect movement in the early spring; furthermore, insect captures were detected outdoors before they were detected inside the warehouse. However, other sites like tree bark, small branches, protected leaf litter, or soil would warm much sooner in the spring and permit the early season immigration observed here. These observations lead us to propose that an alternate overwintering site is a plausible part of the *R. dominica* lifecycle. Generally speaking, members of the Bostrichidae are wood eaters as both larvae and adults, and *R. dominica* is hypothesized to have also occurred in a woody habitat prior to becoming a pest in storage structures (Potter, 1935). *Prostephanus truncatus* reproduces in non-agricultural hosts and stored maize in Africa (Nansen et al., 2004), and outdoor *P. truncatus* captures have been correlated with infestation in nearby maize stores suggesting dispersal (Birkinshaw et al., 2002). In ecological terms, the early spring flight of these pests could be viewed as dispersal from the overwintering grounds and the late autumn flight peaks could be viewed as dispersal behavior to find an appropriate overwintering site. This hypothesis remains to be confirmed.

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